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Abstract: There is an increased interest in the use of poultry litter as fuel by the relevant industries. Hence the environmental impacts of using turkey litter as fuel to generate electricity instead of using litter as fertilizer were systematically analysed for the first time. For this purpose, a systems modelling-based Life Cycle Assessment approach was used, with data obtained directly from the UK turkey industry. Impacts were calculated per 1000 kg turkey live weight produced at the farm gate (functional unit). The avoided burdens method was used to quantify the effects of the alternative litter use. Differences in the environmental impacts between the two litter use scenarios resulted from the combined effect of the following sub-processes: the loss of nitrogen as a crop fertiliser, the transport for collecting litter and distributing the ash as a phosphorus and potassium fertiliser, displacement of electricity generation by a combined cycle gas turbine, specific trace gas emissions from combustion and the loss of soil carbon from the reduced organic matter supply to arable soils. The results showed that there are substantial environmental benefits from using turkey litter as a fuel to generate electricity rather than using it directly as a fertiliser with reductions in burdens of cumulative primary energy demand (14%), eutrophication potential (55%) and acidification potential (70%). The reduction in acidification and eutrophication potentials were mainly associated with reduced ammonia emissions from the storage and land spreading of the litter. Reductions in greenhouse gas emissions were small (3%) because losses of soil carbon as a result of not applying litter to land partially compensated the benefits of reduced fossil energy use. Small increases in nitrogen oxides, volatile organic carbon, particulate matter below 10 µm aerodynamic diameter and dioxin emissions were found, although only nitrogen oxides were especially linked to combustion. Despite its potential benefits, stringent management, monitoring and regulation of biomass fuelled power production is still needed, given the potential hazards of local high emissions. Although turkey litter was analysed in this study, similar results can be expected for broiler litter use as a fuel, as long as geographical conditions are similar.

Environmental benefits of using turkey litter as a fuel instead of a fertiliser

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Abstract

There is an increased interest in the use of poultry litter as fuel by the relevant industries. Hence the environmental impacts of using turkey litter as fuel to generate electricity instead of using litter as fertilizer were systematically analysed for the first time. For this purpose, a systems modelling-based Life Cycle Assessment approach was used, with data obtained directly from the UK turkey industry. Impacts were calculated per 1000 kg turkey live weight produced at the farm gate (functional unit). The avoided burdens method was used to quantify the effects of the alternative litter use. Differences in the environmental impacts between the two litter use scenarios resulted from the combined effect of the following sub-processes: the loss of nitrogen as a crop fertiliser, the transport for collecting litter and distributing the ash as a phosphorus and potassium fertiliser, displacement of electricity generation by a combined cycle gas turbine, specific trace gas emissions from combustion and the loss of soil carbon from the reduced organic matter supply to arable soils. The results showed that there are substantial environmental benefits from using turkey litter as a fuel to generate electricity rather than using it directly as a fertiliser with reductions in burdens of cumulative primary energy demand (14%), eutrophication potential (55%) and acidification potential (70%). The reduction in acidification and eutrophication potentials were mainly associated with reduced ammonia emissions from the storage and land spreading of the litter. Reductions in greenhouse gas emissions were small (3%) because losses of soil carbon as a result of not applying litter to land partially compensated the benefits of reduced fossil energy use. Small increases in nitrogen oxides, volatile organic carbon, particulate matter below 10 μm aerodynamic diameter and dioxin emissions were found, although only nitrogen oxides were especially linked to combustion. Despite its potential benefits, stringent management, monitoring and regulation of biomass fuelled power production is still needed, given the potential hazards of local high emissions. Although turkey litter was analysed in this study, similar results can be expected for broiler litter use as a fuel, as long as geographical conditions are similar.

Table of abbreviations

	Description	Usual unit
AP	Acidification Potential	kg SO_2e
ARU	Abiotic resource use in antimony equivalents	Sb Equ., kg
CED	Cumulative energy demand as primary energy	MJ or GJ
EP	Eutrophication Potential,	kg $PO_4^{3-}e$
GHG	Greenhouse gas	
GHGE	Greenhouse gas emissions	
GWP_{100}	Global Warming Potential over 100 years	kg CO_2e
NMVOC	Non-methane volatile organic carbon	kg
NOx	Nitrogen oxides, NO and NO_2	kg
PAH	Poly aromatic hydrocarbons	kg
PM 10	Particles below 10 μm aerodynamic diameter	kg
t-p-d Equ.	2,3,7,8-tetrachlorodibenzo-p-dioxin, used as equivalent for all dioxins	kg
PAN	Plant available N	
Org-N	Organic N	

1. INTRODUCTION

Poultry litter in the UK (mainly coming from broiler, egg and turkey production) was normally managed only as a fertiliser and soil conditioner until the late 1990s. The high plant nutrient nitrogen(N), phosphorus (P) and potassium (K) concentrations make it more valuable than other (semi-) solid manures (Defra, 2010). The nutrient contents of turkey and broiler litter are very similar and Defra (2010) does not differentiate between their compositions. Turkey and broiler litter includes some bedding, usually wood shavings or chopped straw. Losses of N during litter storage may occur, which can lead to substantial emissions of ammonia (NH_3), and a mixture of di-nitrogen (N_2), nitrogen oxide and dioxide (NOx) and nitrous oxide (N_2O). These change the actual amount of N available when applied to land and hence the fertiliser value. Here, we use turkey litter as an example of the consequences of using the litter as fuel, instead of applying it to land. Similar arguments apply to the use of broiler litter as fuel, but we had better access to key aspects of turkey litter management activity data and hence report this rather than broiler litter.

UK turkey annual production increased from the 1970s to a maximum of 40 M birds in 1995, steadily fell to about 15 M in 2007, and then remained relatively constant (Defra , 2014). The production of turkey litter from 17.5 M slaughterings in 2013 was 0.9 Mt, which contained 21 kt N, 7.7 kt P (or 17.6 kt phosphorus pentoxide [P_2O_5]) and 13 kt K (or 15.7 kt potassium oxide [K_2O]), using the composition data from Defra (2010). There are poultry (of all species) across most of the country, with higher concentrations in some parts, e.g. East Anglia, which also supports a large fraction of UK turkey production (Figure 1). This has contributed to pressures in the nitrate vulnerable zones (NVZ) that were introduced as implementation of the 1991 EU nitrates directive, which became more stringent since being introduced.

Two important features affect the application of manure as a fertiliser: an upper limit on N applied per ha and the exclusion of applications in late autumn and early winter (Defra, 2013). With high concentrations of poultry in some areas, finding an alternative to land application consequently became attractive to farmers. This was enhanced by the potential of using litter as a fuel, which added to the UK's use of renewable biomass for generating electricity. The use as fuel started in 1992 and consumed about 13% of UK poultry litter, with the proportion increasing to a current value of about 35% (data used in the UK ammonia inventory, T.H. Misselbrook, *Pers. Comm.*). Poultry litter has been used in the Netherlands for electricity generation since 2008 (BMC Moerdijk (2008), Lynch et al. (2013) and Quiroga et al. (2010) and investigated the properties of poultry litter as fuel by direct combustion. Jia and Anthony (2011) examined co-combustion of poultry litter and coal. More work seems to have addressed the performance of gasification or pyrolysis of poultry litter (e.g. Di Gregorio et al. (2014), Font-Palma (2012), Huang et al. (2015) and Striūgas et al. (2014). These studies focussed on the technological performance of processes.

Sandars et al. (2003) were the first authors to apply life cycle assessment (LCA) to manure management in the UK, in this case, land application by different technologies. Reijnders and Huijbregts (2005) applied LCA to burning animal wastes in the European Union, including litter and other materials. They found that the greenhouse gas emissions of burning animal waste were very sensitive to the allocation approach chosen. They did not address indirect effects, such as changes in fertiliser use (and hence production) which could considerably change the emissions of greenhouse gases. They considered that such quantification should be the subject of further research. Billen et al. (2015) compared poultry litter being applied to land as a fertiliser with combustion for electricity generation, in the Netherlands using LCA. Main impacts (and benefits for electricity production) related mainly to reduced greenhouse gas from fossil fuel use and emissions of ammonia, nitrous oxide. Further benefits arose from the enhanced ability to export P and K fertiliser in ash away from areas that were potentially over-supplied.

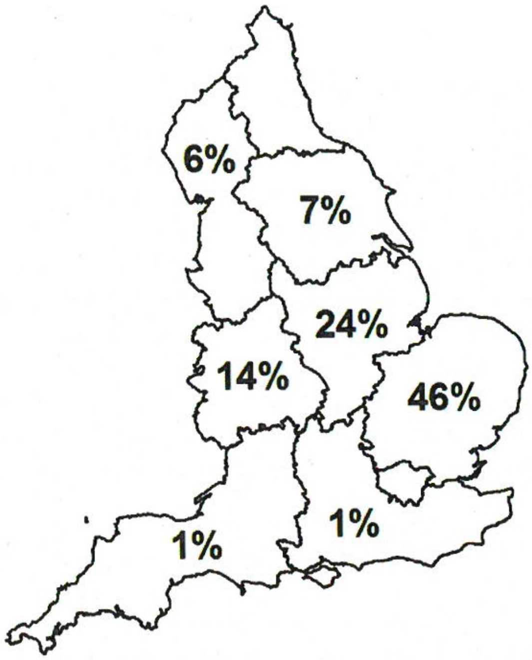

Figure 1 Distribution of turkey farms in England showing regional concentration in the East.

The aim of the current study was to apply a Life Cycle Assessment (LCA), **"from cradle to gate"** to quantify the potential changes in environmental burdens when the turkey litter is used as fuel to generate electricity instead of its traditional use as a fertiliser. A typical UK turkey production system was used as a framework of the analysis (Leinonen et al., 2015).

2. METHODS

2.1. Scope of the LCA

The system boundary included all feed production (with associated upstream inputs) and husbandry activities to produce turkeys up to the farm gate. The alternative approaches to manure management were included within the system boundary. The functional unit (FU) was 1000 kg turkey live weight at the farm, ready for slaughter.

2.2. Systems approach and the turkey production data

Some empirical activity data was supplied from the turkey industry and other partners, but systems modelling was used to provide most the inputs for life cycle assessment This included structural models of the industry, process models and simulation models that were unified in the systems approach such that changes in one area caused consistent interactions elsewhere (Williams et al., 2006). This approach was applied to all subsystems modelled, including crop production, non-crop nutrient production, feed processing, turkey breeding, turkey brooding and finishing plus manure and general waste management, following the approaches in Leinonen et al. (2014), Williams et al., (2006), Leinonen et al. (2012a) and Leinonen et al. (2012b).

A typical, mainstream UK turkey production system was thus represented, producing predominantly stags (males) in controlled-ventilated houses (Leinonen et al., 2014). Farm energy consumption for heating, lighting, ventilation and feeding was based on average data from typical farms. Liquefied petroleum gas (LPG) was used for heating and electricity for everything else. Information on types and amounts of bedding and other materials used was also obtained from the industry. The bird performance and production data, including the length of the production cycle, stocking density, final weight, feed intake and mortality came also from actual farm data. The main production figures are shown in Table 1 and include average bird performance and feed intake and farm energy and material consumption. Additional data, e.g. life cycle inventories (LCI) of machinery, came from Williams et al., (2006). Representative baseline diets were used in the model and these were constructed using turkey industry data (using five-stage phase-feeding). UK-grown wheat was the main energy source in all diets and South American soya bean meal was the main protein source. In addition, the nutrient content of the diets was balanced with minerals and pure amino acids as additives, and a small amount of vegetable oil as an additional energy source. The environmental impacts arising from feed production were calculated based on the relative proportion of each ingredient in the overall diets and its modelled life cycle inventory (LCI) values, obtained with a separate crop model (Williams et al., 2006, 2010).

Table 1

The average production data for the turkey system modelled in this study.

Age at slaughter, days	133
Weight at slaughter, kg	15.2
Feed conversion ratio, kg feed per kg live weight	3.1
Farm electricity use, kWh per slaughtered bird	3.5
Farm LPG use, litres per slaughtered bird	1.6
Bedding used, kg per slaughtered bird	4.4

N, P and K contents of the manure were calculated by the mass balance principle, i.e. the nutrients retained in the animal body were subtracted from the total amount of nutrients supplied by the feed. A separate sub-model was also used for manure and the nutrient cycle, in which the main nutrients applied to the soil in manure were accounted for as either crop products or losses to the environment. The benefits of N, P and K remaining in soil after land application of manure were credited to poultry by offsetting the need to apply fertilizers to winter wheat as described below.

A sub-model quantified the environmental impacts of the main feed ingredients from primary production to processing and delivery (Williams et al, 2010). Greenhouse gas (GHG) emissions (GHGE) from direct land use change were accounted for using the principles of the carbon footprinting method PAS 2050:2011 (BSI, 2011) as applied in Leinonen et al. (2013).

2.3. Modelling the use of poultry litter as fertilizer

Quantifying the environmental burdens of manure management followed the principles of Sandars et al. (2003) as implemented by Williams et al. (2006). All the emissions from the time of excretion to land spreading are summed to derive the negative impacts against the livestock (or debits). The energy used for machinery manufacture and diesel used in manure management are also debited; the latter includes transport to arable farms and litter spreading. The N in manure has a benefit of increasing crop yield, and is treated in two parts in the model. Plant available N (PAN) is the sum of ammoniacal-N, uric acid-N and 10% of the remaining organic N (Org-N). PAN is assumed to be available to crops in the year of application (Chambers et al., 1999) and the residual Org-N gradually degrades over time to become PAN.

The long-term yield response of winter wheat to manure N is modelled as a combined effect of the PAN and Org-N, along with associated long-term losses from leaching and denitrification. The yield increment is equated to the same yield response from a mass of ammonium nitrate in non-organic systems. This is credited back to livestock as the burden of producing, delivering and applying the same mass of ammonium nitrate along with full credits for the P and K in manure, which displaces the need for equivalent amounts of manufactured P and K.

The litter is split into proportions that can be applied directly either without storage or (mainly) with storage. The proportions of these two components were assumed to be those used in the UK ammonia inventory (T.H. Misselbrook, *Pers. Comm.*). It can be expected that some storage of litter is inevitable given nitrate vulnerable zone regulations (Defra, 2013) and the general wish to apply litter when it is most suitable agronomically.

The effects of organic matter in litter and associated benefits for soil carbon are addressed in section 2.4.3.

In summary, the burdens from emissions and energy use for litter management are balanced against the benefits of offsetting the need for manufactured fertilisers by using the plant nutrients in litter.

2.4. Management of litter used as a fuel

In contrast to use as fertiliser, litter is transported to power stations and the energy liberated is used to generate electricity. The residue is used as a fertiliser that contains only P and K.

2.4.1. Transport and ammonia

After birds are harvested, litter is rapidly removed by contractors and transported by lorry to the power station for immediate (or near-immediate) incineration. Litter is stored at power stations in low loss stores that are required under the waste management regulations, hence are negligible sources of ammonia emissions, in contrast to on-farm stores.

2.4.2. Generation of electricity

The net electricity export generated from poultry litter was estimated to be 0.31 kWh [kg fresh weight]$^{-1}$ (EPRL, 2014). This included all the internal uses of electricity together with constraints on supply to the National Grid, which is managed by the Office of Gas and Electricity Markets (https://www.ofgem.gov.uk/).

The trace gas and particulate matter emissions from litter combustion were obtained from the National Atmospheric Emissions Inventory (NAEI, 2014), which gives values for biomass-burning power stations. The trace gases included: NO_X, N_2O, carbon monoxide (CO), sulfur dioxide (SO_2), non-methane volatile carbon (NMVOC), methane (CH_4), particulate matter < 10 μm (PM_{10}) and dioxins.

All carbon dioxide (CO_2) from combustion was considered to originate from short term-biomass and as such does not contribute to net *de novo* CO_2 emissions from long-term stored carbon (C). The combusted biomass includes the excreta, feathers etc from birds themselves and the straw and wood chips used as bedding. These are derived from crops or trees in which the short term uptake of CO_2 into C is not accounted for in the life cycle inventories (LCI). This is consistent with Note 1 of Section 7.9.5 in PAS2050 (BSI, 2011).

Electricity production from litter was compared with the most recent conventional combustion technology, i.e. the marginal supply, as opposed to the current grid average. The comparison is thus based on the examination of two alternative sources of new generating capacity. In the UK, the conventional technology is a combined cycle gas turbine (CCGT) that would run on natural gas, so it was assumed that each unit of electricity exported from the biomass plant displaces the need for electricity from a CCGT. The efficiency of CCGT was taken as 51% (Lelyveld and Woods, 2010), with 2.9% losses in accessing the national grid (Appendix 1). It takes 1.02 MJ of primary energy to extract and deliver 1 MJ (lower heating value, LHV) of natural gas to users (ELCD, 2014). Hence, the net energy conversion in a CCGT (including internal use of power) is 2.05 MJ uncompressed natural gas (as primary energy) per MJ exported electricity..

There are no residues from a CCGT, but combustion of litter leaves P and K in ash. All ash was assumed to be used as fertiliser and therefore P and K could be utilized as plant nutrients. It was assumed that in the long term, all P and K will become plant available, although in the short term P availability is reduced by the high temperatures during combustion. The credit for P and K was based on replacement of rock P and K fertilisers and the transport distance to farms was assumed to be 250 km. The transport burden includes the additional weight of minerals in the ash apart from the elemental P and K themselves. The sum of P and K was estimated at 17% of total ash weight from a range of commercial products (Fibrophos, 2014).

2.4.3. Soil C balance

When the litter is burnt, that source of organic C input into (typically arable) soils is lost and if continued, leads to a loss of C from soil (and thus generation of CO_2 emissions) until a new equilibrium is established. The effect of this process was analysed using the RothC soil C simulation model (Coleman, 2005) as follows. The soil C equilibrium was calculated for a range of arable soils soil types mainly in eastern England (represented by five sites: Cranwell, Downham, Rothamsted, Wellesbourne and Woburn) growing winter wheat and assuming an application of 1 t (fresh weight) litter every year (Table 2). This baseline was selected arbitrarily, but the result would be the same for any application rate, as the absolute amount of the decomposing organic matter has no effect on its turnover time.

Table 2

Values used to estimate the C concentration in turkey litter (Defra, 2010, Coleman, 2005 and this study).

Item	Value
Dry Matter (DM) concentration in fresh weight (FW)	65%
Volatile Solids (VS) in DM	80%
C in VS	50%
Weight of C in 1 unit litter	0.26

After establishing an equilibrium in which litter was supplied every year, the supply of litter was set to zero and the consequent decline in soil C was simulated by the model to give an exponential decline leading towards an asymptote and thus giving the new soil C equilibrium value

$$C_t = a + b\, e^{-kt} \qquad (1)$$

In which, C_t is the density of C in soil (t/ha) at time, t (in years), *a* and *b* are constants such that *a* is C at the new equilibrium, *a* + *b* is the C density when t=0, i.e. at the initial equilibrium (just before the end of manure applications) and k is the rate constant.

As the proportion of the litter C remaining in the soil is dependent on the timescale in consideration, a range of timescales was investigated, namely 20, 50, 100, 250 and 500 years and t_{90}, which is the time needed to reach a 90% change towards equilibrium.

2.4.4. Summarising manure management as fertiliser

In summary, the burdens of transporting litter to power stations, trace combustion emissions, loss of soil C and transporting P and K in ash to farms are balanced against the reduced need for natural gas to generate electricity, lower ammonia emissions from manure storage and the reduced need for manufactured P and K fertiliser.

2.5. Other data and environmental impacts categories

The life cycle inventory data not previously specified, e.g. for diesel and natural gas, came from the European Life Cycle Database (ELCD, 2014).

Emissions to the environment were aggregated into environmentally functional groups as follows.

Global Warming Potential (GWP) was calculated using a timescale of 100 years, with 1 kg CH_4 and N_2O equivalent to 25 and 298 kg CO_2 (CO_2e) respectively (Forster et al., 2007).

Eutrophication Potential (EP) was calculated using the method of the Institute of Environmental Sciences (CML) at Leiden University (CML, 2014). The main sources in turkey production are nitrate (NO_3^-) and phosphate (PO_4^{3-}) leaching to water and ammonia (NH_3) emissions to air. EP was quantified as phosphate equivalents.

Acidification Potential (AP) was also calculated using the CML(2014) data. The main sources are ammonia emissions, together with sulphur dioxide (SO_2) from fossil fuel combustion. AP was quantified in terms of SO_2 equivalents.

Dioxin emissions were quantified as 2,3,7,8-tetrachlorodibenzo-p-dioxin equivalents (CML, 2014).

Photochemical ozone creation potential (POCP) was quantified as ethylene equivalents (CML, 2014).

Particles smaller than 10 microns in diameter (PM_{10}) were summed from all data sources used.

In addition, energy use was quantified as cumulative energy demand (CED). This is the sum of all primary energy used and includes all the energy needed for extraction and supply of energy carriers, such as diesel or electricity (CML, 2014).

2.6. Sensitivity analysis method

In the sensitivity analysis, all other variables were held constant while one variable under scrutiny was scaled up and down by 10% (Table 3). It was assumed that turkey production *per se* was unchanged so that only variables relating to litter management were tested.

Table 3

Variables tested in the sensitivity analysis.

Descriptor	Comments
Electricity export	Net amount of electricity supplied to national grid from litter fuelled power station
Soil C	Loss of soil C resulting from litter use as fuel
PK value litter ash	The fertiliser value of P and K in ash from litter
PK value normal litter	The fertiliser value of P and K in land-applied litter
PK (in ash) transport	Burdens of transport of P and K in ash to farms for use as fertiliser
Litter transport to power station	Burdens of transport of fresh litter from farms to power station
Litter transport to arable farm	Burdens of transport of fresh litter from farms to arable farms

In practice, the sensitivity analysis was linear in that 10% increases or decreases in inputs results in changes of equal magnitude (within 0.5%), thus only the effects of increases are reported.

3. RESULTS

3.1. Effect of the use of litter as fuel on soil C content

The time needed to reach a 90% change towards equilibrium (t_{90}) ranged from 174 to 373 years. Hence, New equilibria of soil C were established (or close to establishment) within 500 years after stopping the use of poultry litter as fertilizer for all soils investigated (Figure 2). This is, however, a very long time over which to assume a constant practice. A 20-year timescale is used in PAS2050 (BSI, 2011) and sustainability reporting within the Renewable Transport Fuel Obligation (DFT, 2011). The results show that the differences between the proportions of C lost from soil were relatively slow and small between 20 and 500 years (Figure 2, Table 4).

The mean of the changes over 20 year was thus in further analysis as this was consistent with the timescale used in PAS2050 and DFT (2011) and the scale is similar to the lifetime time of a power plant, during whic h this alternative use of litter is likely to occur.

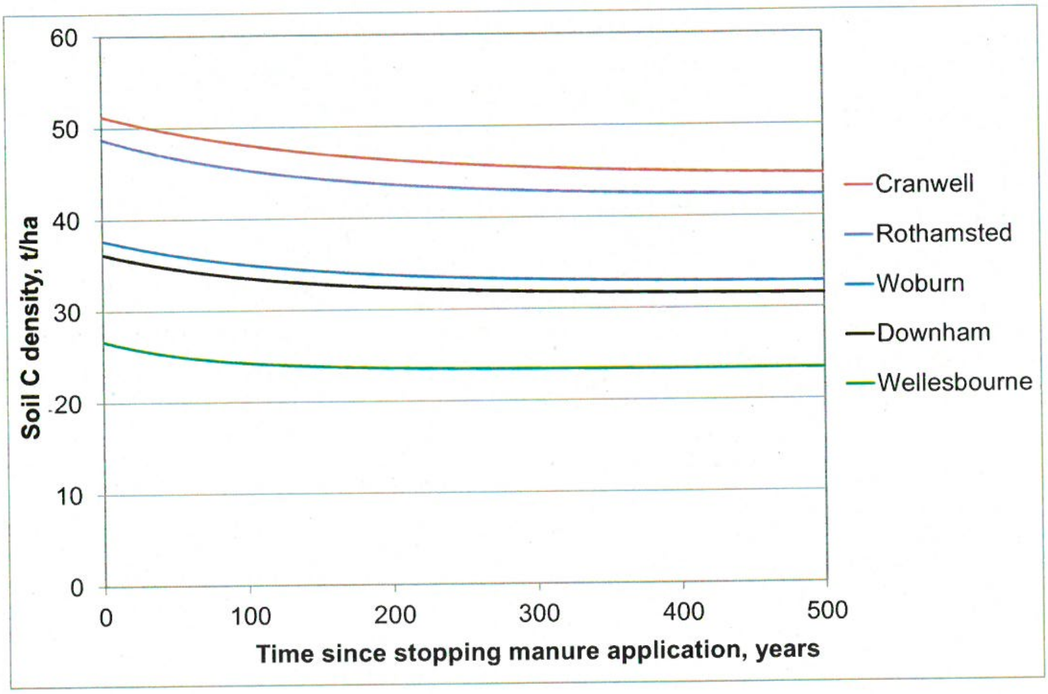

Figure 2 Soil C content after stopping litter applications of 1 t FW/year, as simulated with RothC at 5 sites growing winter wheat in England, UK.

Table 4

Soil C from litter lost and retained in soil derived from simulations with RothC. Results are the means of five sites.

Time, years	20	50	100	250	500
Proportion of C lost from litter	85%	87%	89%	93%	96%
Coefficient of Variation	2%	2%	2%	2%	2%

The decline in soil C density is related to the proportion of litter C that is retained in soil. Over 20 years, the loss of soil C is equivalent to 28% of C in litter that would have been applied in the original equilibrium state, i.e. 0.053 t C [t litter]$^{-1}$. This was converted to kg CO_2e as 0.053 * 1000 * 44/12, i.e. 195 kg CO_2e [t litter]$^{-1}$. The net effect of this analysis was to add a further 338 kg CO_2e emissions from soils per t live weight of turkeys (i.e. arising from 1.73 t litter per t live weight).

3.2. Effect of the litter management scenarios on environmental impact categories

The results show substantial environmental benefits from using litter as a fuel compared with direct land application as fertiliser (Table 5). The biggest relative effects are from eutrophication and acidification potentials (about 55% and 70% reductions respectively), which result from eliminating ammonia emissions during storage and land spreading, summing to a 75% reduction overall. The saving in cumulative energy demand (which is 99.5% non-renewable with litter as a fertiliser) is about 14% with the fuel use option and this is reflected in a 14% decrease in abiotic resource use. The proportion of renewable energy of the total energy use in turkey production increased to 2%. The effect on reducing GHGE (or the carbon footprint), is, however small at only 3%. The largest contribution to the effect on reducing CED is from offsetting gas for generating electricity. In contrast, the saving in GHGE from electricity generation is the same magnitude as the loss of soil C from not applying litter to land. Hence, the net effect was relatively small.

There were also some negative effects of using litter as a fuel: NOx emissions increased by 64%, NMVOC by 12%, PM_{10} by 8% and dioxins by 4%. None of these are welcome, but not all of these increases arise directly from litter combustion itself. These four emissions were greater from turkey production *per se* (i.e. without litter management) than with normal litter management, i.e. normal litter management as a fertiliser reduced net emissions. Using litter as fuel also reduced net emissions of dioxin and PM_{10}, but less than litter used as fertiliser. In both cases, the offsetting of fertiliser value or electricity against other burdens effectively created negative emissions. With both NMVOC and NOx, there were indeed net increases from litter combustion, with 10% and 39% of total emissions (per FU) respectively from combustion itself (

Table 6). In contrast, 1% and 5% of dioxin and PM_{10} emissions respectively were from combustion itself. Most of the carbon monoxide emissions (75%) result from litter combustion.

Table 5

The environmental burdens per 1000 kg live weight of turkeys at the farm gate, with the baseline scenario (litter use as fertilizer) and the effects of the alternative litter use as fuel to generate electricity.

	CED, GJ	GWP_{100}, kg CO_2 e	EP, kg PO_4^{3-}e	AP, kg SO_2e	ARU, Sb, kg	NMVOC, kg	Dioxins, kg t-p-d Equ.	Particles, kg PM 10	NOx as NO_2, kg	NH_3, kg N	N_2O-N, kg N
Turkey without manure management	21.6	4,244	14	24	12	6.8E-01	1.8E-08	1.E-01	2.08	8.88	4.30
Litter as fertiliser per FU	-1.04	261	18	60	-0.63	-1.3E-02	0.00%	-1.E-02	-0.07	26.4	0.31
Turkey with litter as fertiliser	20.6	4,505	32	84	11	6.7E-01	1.7E-08	1.E-01	2.01	35.3	4.62
Litter as fuel per FU	-3.95	137	0	0	-2.1	6.8E-02	0.00%	-4.E-03	1.22	0.00	0.04
Turkey with litter as fuel per FU	17.7	4,380	14	24	9.9	7.5E-01	1.8E-08	1.E-01	3.29	8.88	4.35
Reduction in burdens of turkey production with litter as fuel	14%	3%	55%	71%	13%	-12%	-4%	-8%	-64%	75%	6%

Table 6

Proportion of total emissions of individual compounds and aggregated equivalents from litter combustion as monitored by the Environment Agency.

Compound or equivalents	Proportion of total emissions from combustion itself	Comments
Dioxins	1%	
NOx	39%	
PM 10	5%	
NMVOC	10%	
CO	75%	All contribute to GWP
CH_4	19%	
N_2O	1%	
GWP $_{100}$	1%	
Acidification potential	2%	

3.3. Sensitivity analysis results

The effects of changing litter management variables were examined for the effects on the alternative impacts per unit mass of litter and on the overall outcome of the LCA with the functional unit of 1000 kg LW (Section 2.6). Note that some values are negative, because of the balances in litter management, e.g. fertiliser value vs management activity for litter as fertiliser. Thus, increasing an input may decrease the output. The signs are shown for completeness, but the magnitudes are arguably more important.

For litter as fertiliser, changing the N concentration in litter had an even effect across most burdens, while increasing the litter transport distance had the largest effect on NOx and otherwise had similar effects changing to N concentrations except for categories related to ammonia and PM_{10} (Table 7). The PK fertiliser value had most effect on CED, but also had large effects on dioxins, PM_{10} and NOx.

With litter as fuel, the electricity exported had large effects on most burdens, except for dioxins (Table 8). The main influence on GWP was loss of soil C, which did not affect other categories and was of a similar magnitude to electricity export, but with the opposite sign. The PK fertiliser value of litter had the largest effects on ammonia related burdens and dioxins. The two transport terms had the least effects.

Table 7

Effect of 10 percent change in input on percentage change in burdens for litter managed as a fertiliser (excluding other burdens of turkey production). Values below 0.1 percent are shown as 0.

Litter as fertiliser	CED	GWP	EP	AP	ARU	NMVOC	Dioxins	PM_{10}	NOx	NH_3	N_2O
N concentration in litter.	1.8	-1.0	-1.0	-1.7	1.7	1.7	1.8	0	0.1	-1.7	0.4
PK fertiliser value (litter as fuel)	2.9	-0.8	0	0	3.3	3.3	5.0	5.7	8.4	0	0
Litter transport to arable farm	-1.4	0.4	0	0	-1.1	-1.1	0	0	-11	0	0

Table 8

Effect of 10 percent change in input on percentage change in burdens for litter managed as a fuel (excluding other burdens of turkey production). Values below 0.1 percent are shown as 0.

Litter as fuel	CED	GWP	EP	AP	ARU	NMVOC	Dioxins	PM_{10}	NOx	NH_3	N_2O
PK fertiliser value (litter as fuel)	0.8	-1.3	8.3	-9.0	1.0	1.0	13	17	-0.5	27	0
Litter transport to power station	-0.4	0.8	-0.1	0.2	-0.4	-0.4	0	-0.1	0.7	-15	0
PK transport after combustion	-0.3	0.6	-0.1	0.2	-0.3	-0.3	0	-0.1	0.5	-11	0
Electricity exported	9.9	-15	1.9	-4.3	9.6	9.6	0	7.2	-1.2	8.3	-0.1
Soil C	0	23	0	0	0	0	0	0	0	0	0

Some similar trends were seen when considering the responses of the whole LCA (Table 9), but these were generally of similar magnitude, given the large constant terms from turkey production *per se*. The N concentration in litter for fertiliser had the largest effect on ammonia and related impacts, including the largest single response with eutrophication potential. Electricity export had the largest effect on CED and had the second highest effect on GWP after soil C. All three transport terms all had relatively small effects, with NOx being the largest, although electricity exported had the largest effect on NOx.

Table 9

Effect of 10 percent change in input on percentage change in burdens for the whole turkey production chain including net litter management. Values below 0.1 percent are shown as 0.

	CED	GWP	EP	AP	ARU	NMVOC	Dioxins	PM_{10}	NOx	NH_3	N_2O
N concentration in litter.	0.1	0.1	-5.5	-2.9	0.1	0.1	0.1	0	0	-2.6	0
PK fertiliser value (conventional management)	0.2	0	0	-0.1	0.2	0	0.3	0.6	0.2	0	0
Litter transport to arable farm	-0.1	0	0	0	-0.1	0	0	0	-0.2	0	0
PK fertiliser value (litter as fuel)	-0.2	0	0	0.1	-0.2	0	-0.3	-0.6	-0.2	0	0
Litter transport to power station	0.1	0	0	0	0.1	0	0	0	0.3	0	0
PK transport after combustion	0.1	0	0	0	0	0	0	0	0.2	0	0
Electricity exported	-2.0	-0.5	0	0	-1.8	0	0	-0.2	-0.4	0	0
Soil C	0	0.8	0	0	0	0	0	0	0	0	0

4. DISCUSSION

Substantial environmental benefits from using turkey litter as a fuel for generating electricity were demonstrated. We know of no directly comparable studies, despite the widespread use of the practice. Huang et al. (2015) examined the economics and technical feasibility of using poultry litter in Northern Ireland as a biofuel though pyrolysis and gasification, but this was based on simulations modelling and did not quantify GHG emissions, although it suggested considerable promise in the approach. The practice, however, and its consequences are frequently questioned both in the popular press and trade literature (e.g. NFU, 2014). Reijnders and Huijbregts (2005) addressed GHG emissions from burning animal wastes in Europe, including animal meal and litter. Much focus was on the extra fossil fuel needed to produce the litter. They obtained contrasting results from either energy-based or economic allocation. In contrast, we used the avoided burdens method, which removes the arbitrariness of allocation and hence gives a more robust result (BSI, 2006).

There are concerns about trace gas emissions around power stations, which were examined by Henihan et al. (2003). They found that ground level concentrations of NOx, SO_2 and CO were all within the limits and guidelines for air quality around a combustion plant. They did not, however, quantify dioxin emissions, which were marginally increased in our study with litter combustion. We have shown that most dioxin emissions, however, do not occur at the point source of the power station. In contrast, most carbon monoxide and about half of NOx emissions are concentrated at the power station. This agrees with the findings of Henihan et al. (2003). Nonetheless, existing power stations in Britain are licenced, monitored and regulated by the respective environment agencies. It is thus reasonable to deduce that no significant health hazard exists, but it is clear that great care must be taken over the management and monitoring of such facilities. There is no room for complacency.

Although the principal environmental interest of many stakeholders is the carbon footprint, the benefits for reducing GHG emissions are small when poultry litter is used as fuel. The benefit of reduced CO_2 emissions from electricity production is roughly balanced by the loss of soil C. However, the benefits for reducing CED and non-renewable energy use are substantially higher (and are thus linked with abiotic resource use). There is still a clear dependency on fossil energy in the background processes that lead to delivery of litter to the power station. It is thus somewhat questionable whether the term renewable energy can fully be applied to this process.

Our results for GHG emissions are less favourable for electricity generation than those of Billen et al. (2015). There are two main reasons for this. They did not account for loss of soil C by removing litter from land application and their main comparison was with coal-based electricity generation, which is more GHG intensive than gas generation. Further, their substitution of synthetic N fertiliser was based on the total N concentration in litter, whereas ours was based on the long-term yield response from the N fractions in litter. The latter applies a more rigorous substitution of N and would thus give litter lower credits for the avoided burdens of synthetic N production and use.

The main benefits of using litter as fuel are associated with reduced ammonia emissions and the consequent effects on AP and EP, which are the major environmental impacts arising from poultry production (Leinonen et al., 2012a; 2014; Leinonen and Williams, 2015). Land application of manure also contributes to nitrate leaching and aquatic eutrophication. The Convention on Long-Range Transboundary Air Pollution (CLRTAP) led to the 1999 Gothenburg Protocol to abate acidification, eutrophication and ground-level ozone, which was implemented by the EU National Emission Ceilings directive (2001/81/EC (NECD) 2001), thus all EU countries have binding targets to reduce ammonia (and other) emissions and using litter as a fuel contributes to this. This agrees with the findings of Billen et al. (2015).

A disadvantage of litter combustion is that less C gets into arable soils, which already lost C since the Second World War, e.g. by major changes from mixed to dominantly arable farming (Bellamy et al.

2005). Soil C helps maintain structure and supports active microbial communities. It acts as a store for C while management practices support it, but change in practices can cause subsequent losses of stored soil C. The balance of GHGE shows that despite the loss of C in soil storage with combustion, this does not lead to a net increase in GHG emissions when the whole production system is taken into account. We only considered a range of soils from England, where most turkey production is found. The rate of decay of C depends on the clay content of soil and climate. The balance may thus be different in other areas. The sensitivity analysis clearly showed the importance of the loss of soil C. It should, however, be noted that the expected changes in the soil C content may differ depending on the assumptions of the soil C model used in the analysis. The RothC soil C model, which was applied in this study, has been extensively used across the world and compared with measured changes in diverse ecosystems, e.g. Cerri et al. (2003). This reinforces our confidence in the other main term addressing the net GHG emissions, namely the loss of soil carbon as a result of alternative use of poultry litter.

One limitation of the use of poultry litter as a fertiliser is its high nutrient concentration. Providing a large supply of C (to maintain the soil C storage) will be limited by the danger of an oversupply of N, P and K. Indeed, the high N concentration in litter is one motive for using litter as a fuel.

The benefits for ammonia emissions are considerable when the litter is used as fuel. The current use of turkey litter as a fuel saves about 0.9 kt ammonia emissions a year in the UK. This would be increased by about a further 1.3 kt if litter use for fuel increase to 80% compared with the current estimate of 35%. This would be about four times higher if applied also to broiler litter.

The scale of poultry farming in parts of eastern England has been an economic success for the industry, but this has contributed to some environmental problems and, later, solutions. High ammonia emissions from litter are one problem as well as eutrophication. The high concentrations of poultry in parts of eastern England (plus other available biomass, like straw) also renders the solution of fuel use an economic success, which also has environmental benefits. A more dispersed poultry industry would lead to a less favourable structure for centralised fuel use, with increased transport burdens. However, on-farm fuel use of litter has also become possible in Britain recently through a change in the definition of litter in the waste management regulations. The main driver behind on-farm use is to replace heating fuel with heat from litter. A broadly similar outcome would occur if the small-scale fuel use of litter was analysed in the same way as with centralised power stations. There would be different substitutions, e.g. fertiliser value for heating energy, and no extra transport requirement, so relative magnitudes would differ.

Uncertainties of the estimated environmental impacts of UK turkey production were previously quantified by Leinonen et al. (2015) but these are not reported quantitatively in this study. We consider that there are too many areas in which the uncertainties of the model inputs are unavailable to make a formal uncertainty analysis. However, we have high quality activity data, with the litter collection and bird production data from the largest UK turkey producers, which accounts for about 90% of housed UK turkey production. Litter use by power stations is recorded publicly and used in other areas that require robust data, e.g. the UK GHG inventory. The turkey production systems model is based on extensive data from the industry, including bird growth rates, diets and resource use. The main input variable of the model, i.e. the amount of electricity generated per unit of combusted litter was checked against other data sources. Quiroga et al. (2010) found that the lower heating value of laying poultry manure was 12.1 MJ $[kg\ DM]^{-1}$, hence being 5.8 MJ $[kg\ FW]^{-1}$ at 48% DM. Yassin et al. (2009) analysed fluidised-bed biomass combustion and found an energy efficiency of 22%, giving at electricity output of 0.35 kWh electricity $[kg\ FW]^{-1}$, which is close to the value given by ERPL of 0.31 kWh electricity $[kg\ FW]^{-1}$. This gives considerable confidence in the analysis.

As discussed above, turkey litter was used as the basis of this analysis, because of the high quality activity data available to us. Given the similar plant nutrient contents of broiler litter, similar environmental benefits could be expected using broiler litter as a fuel with similar geographical conditions.

5. CONCLUSIONS

As far as we are aware, this is the first study that systematically compares the environmental impacts of using turkey litter either generate electricity instead or using turkey litter as fertilizer and including turkey production. The results show that there are substantial environmental benefits from using turkey litter as a fuel to rather than using it directly as a fertiliser. The main benefits are from reduced ammonia emissions and saving primary fossil energy by generating electricity from biomass. There is still a substantial input of fossil energy into the electricity produced resulting from use in turkey production and litter collection. The very small decrease in greenhouse gas emissions is the result of a fine balance between the loss of soil C and the displacement of electricity from a marginal combined cycle gas turbine generator. There were, however, small increases in NMVOC, NOx, dioxin, and PM_{10} emissions and such emissions must be managed and regulated in the most stringent way to avoid any hazard to health. The increases in dioxins and PM_{10} were not related to combustion emissions, whereas those of NOx clearly were.

6. ACKNOWLEDGMENTS

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Appendix 1 Post generation losses from a CCGT

The UK Digest of Energy Statistics (DUKES, 2015) describes losses in 2014 as 7.9% of energy demand. The losses comprise three components:

- Transmission losses (6.5 TWh) from the high voltage transmission system
- Distribution losses (21 TWh), which occur between the gateways to the public supply system's network and the customers' meters, and accounted for about 74 per cent of losses
- Theft or meter fraud (1.0 TWh)

It was assumed losses applying here were distribution losses and that half occurred at the generation plant. The proportion of post generation losses (PGL) was estimated at:

$$PGL = \frac{21 \times 0.5}{6.5 + 21 + 1}$$

Hence PGL = 2.9%

Highlights for Environmental benefits of using turkey litter as a fuel instead of a fertiliser

- Turkey litter handling by land application and electricity generation were compared
- Environmental life cycle assessment (LCA) was used as the method
- The main benefits were from a large reduction in ammonia (NH_3) emissions
- Cumulative primary energy demand was reduced by 14%
- Loss of soil C reduced beneficial climate change impacts

Graphical Abstract (for review)

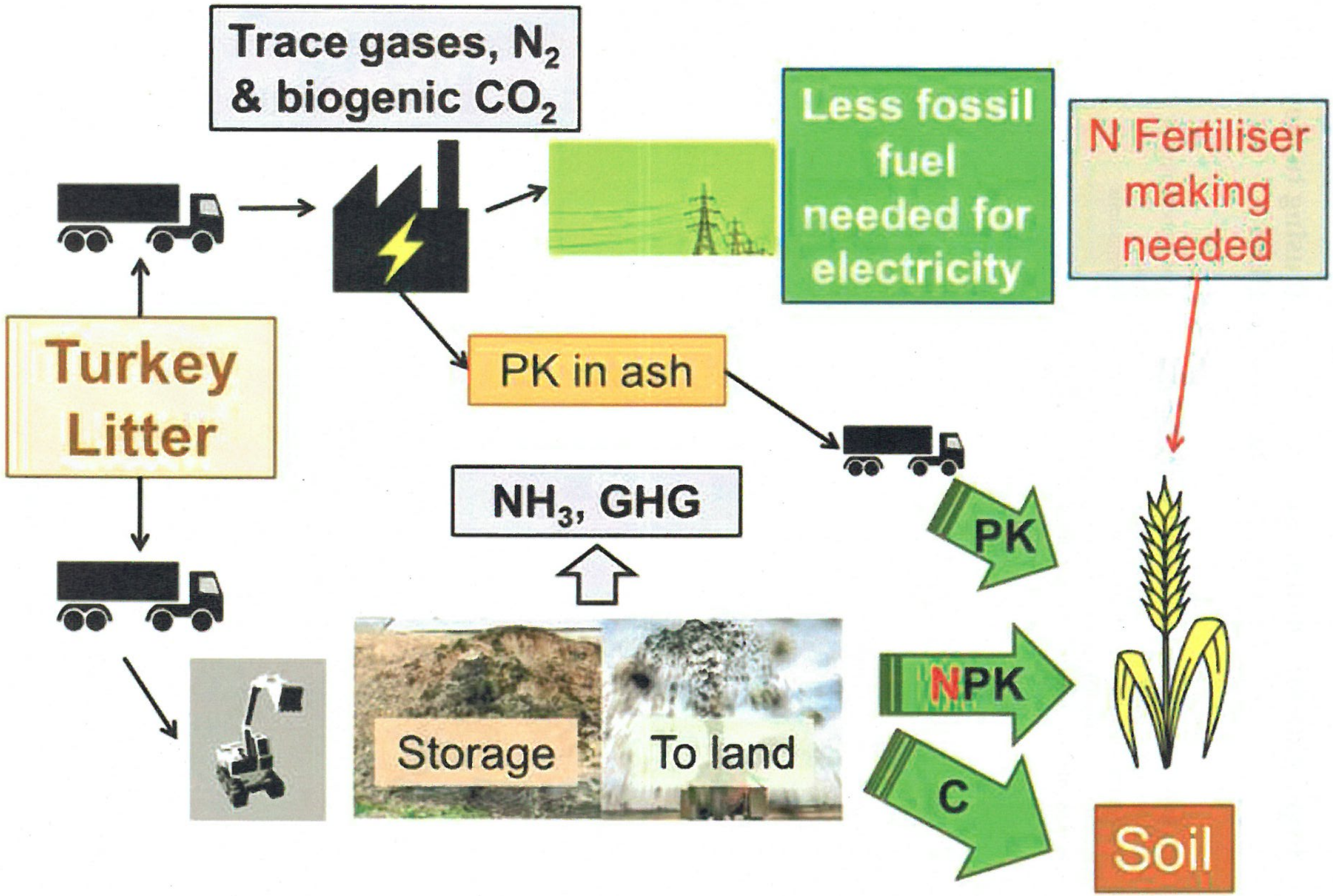

Figure 1

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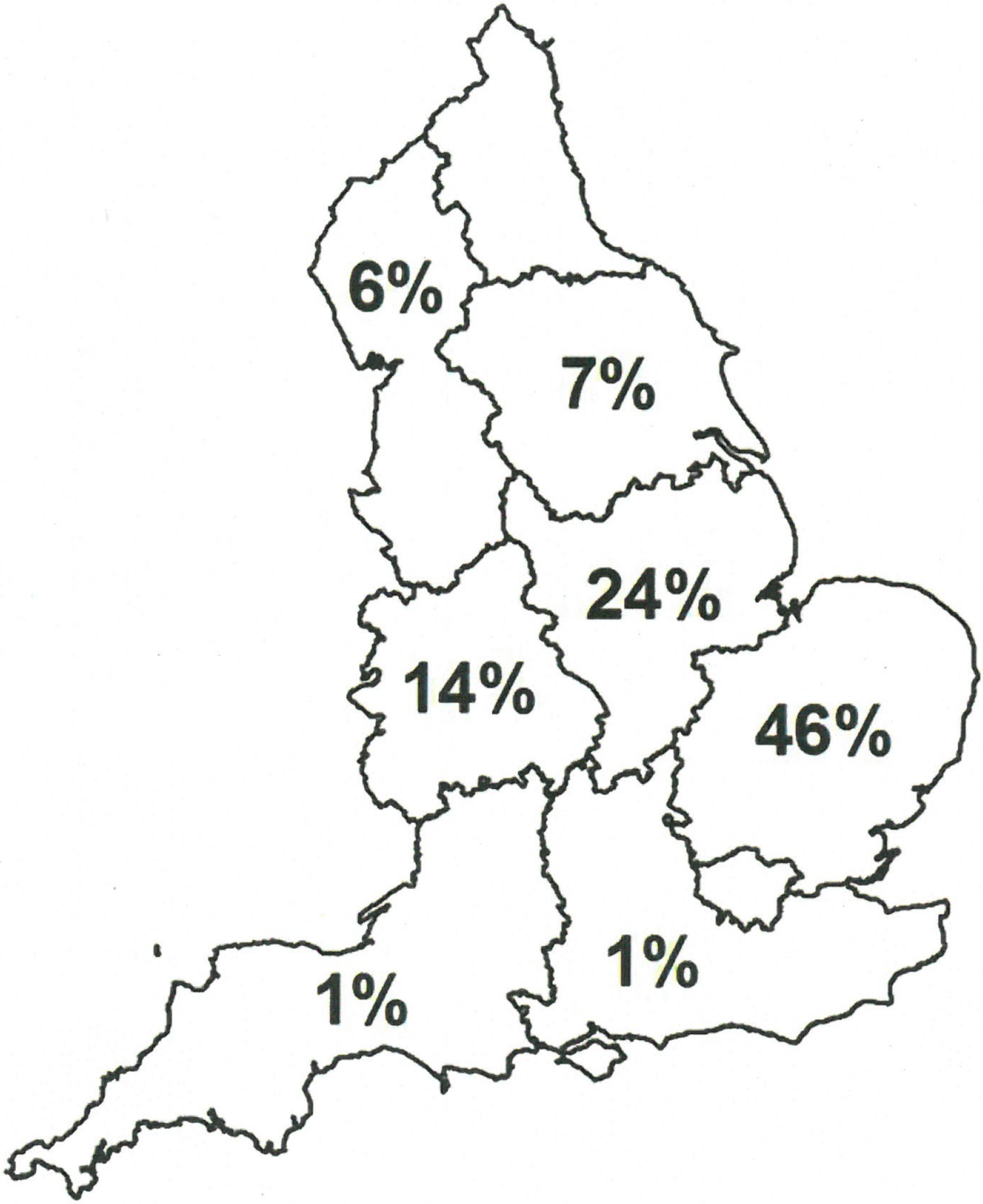

Figure 2

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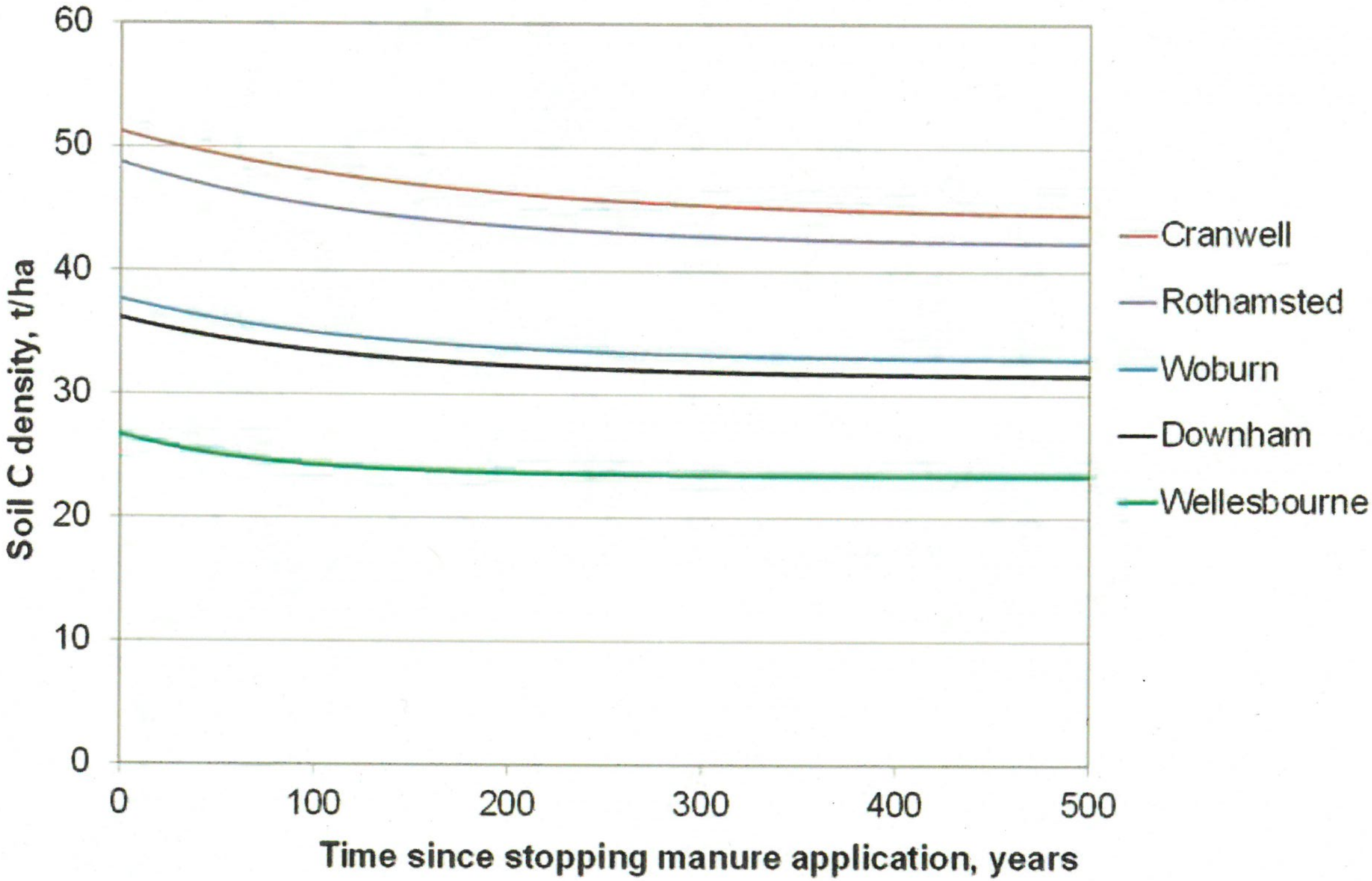

Detailed responses

These were from the assistant editor rather than the reviewers. All were addressed as requested, including producing a colour Figure 2.

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